DOUBLE TRANSVERSE-SPIN ASYMMETRIES IN DRELL–YAN AND J/ψ PRODUCTION FROM PROTON–ANTIPROTON COLLISIONS

M. GUZZI[1,2,3], V. BARONE[4,5], A. CAFARELLA[6],
C. CORIANÒ[1,2] and P.G. RATCLIFFE[3,7]

[1] *Dip. di Fisica, Università di Lecce, 73100 Lecce, Italy*
[2] *INFN, Sezione di Lecce, 73100 Lecce, Italy*
[3] *Dip. di Fisica e Matematica, Università dell'Insubria, 22100 Como, Italy*
[4] *Di.S.T.A., Università del Piemonte Orientale "A. Avogadro" 15100 Alessandria, Italy*
[5] *INFN, Gruppo Collegato di Alessandria, 15100 Alessandria, Italy*
[6] *Dept. of Physics, University of Crete, 71003 Heraklion, Greece*
[7] *INFN, Sezione di Milano, 20133 Milano, Italy*

We perform a NLO numerical study of the double transverse-spin asymmetries in the J/ψ resonance region for proton–antiproton collisions. We analyze the large x kinematic region, relevant for the proposed PAX experiment at GSI, and discuss the implication of the results for the extraction of the transversity densities.

1. Introduction

The purpose of this talk is to illustrate a numerical analysis of the double transverse-spin asymmetries in Drell–Yan processes in the J/ψ resonance region and to discuss the results with regard to the proposed PAX experiment and the possibility of accessing the transversity densities in proton–antiproton collisions.

2. Access to transversity densities

The missing leading-twist piece in the QCD perturbative description of the nucleon is the transversity density,[1] which is defined as the difference of probabilities for finding a parton of flavour q at energy scale Q^2 and light-cone momentum fraction x with its spin aligned ($\uparrow\uparrow$) or anti-aligned ($\uparrow\downarrow$) with that of transversely polarized parent nucleon

$$\Delta_T q(x, Q^2) = q_{\uparrow\uparrow}(x, Q^2) - q_{\uparrow\downarrow}(x, Q^2)\,. \qquad (1)$$

Given its chirally odd nature, transversity may be accessed in collisions of two transversely polarized nucleons (Drell–Yan) via the double transverse-spin asymmetries which are defined as the ratio

$$A_{TT} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} = \frac{\Delta_T \sigma}{\sigma_{\rm unp}} \tag{2}$$

between the transversely polarized and unpolarized cross-sections.

Doubly polarized Drell–Yan production (illustrated in Fig. 1) is the cleanest process for probing transversity distributions. It has recently been suggested that collisions of transversely polarized protons and antiprotons should provide a very good opportunity to determine the nucleon transversity via measurement of A_{TT}.

Double transverse-spin asymmetries depend may only on quark and antiquark transversity distributions

$$A_{TT} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} = \hat{a}_{TT}(\varphi) \frac{\sum_q e_q^2 \, \Delta_T q(x_1, M^2) \, \Delta_T \bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}{\sum_q e_q^2 \, q(x_1, M^2) \, \bar{q}(x_2, M^2) + (1 \leftrightarrow 2)} \, , \tag{3}$$

where $\hat{a}_{TT}(\varphi)$ contains the azimuthal angular dependence

$$\hat{a}_{TT}(\varphi) = \tfrac{1}{2} \cos 2\varphi \tag{4}$$

and M is the dilepton invariant mass.

Measurement of A_{TT}^{pp} in the case of proton–proton collisions is planned at RHIC but the asymmetry is expected to be small (2–3%).[2,3] In fact, A_{TT}^{pp} contains antiquark distributions and the RHIC kinematics ($\sqrt{s} = 200\,\mathrm{GeV}$, $M < 10\,\mathrm{GeV}$, $x_1 x_2 = M^2/s < 3 \times 10^{-3}$) probes the low-$x$ region where, compared to $q(x)$, $\Delta_T q(x)$ is suppressed by QCD evolution. Such problems may be avoided by measuring $A_{TT}^{p\bar{p}}$ in proton–antiproton collisions at lower centre-of-mass energies;[2,4] this is the program of the PAX experiment at GSI.[5] For the GSI kinematics we have $s = 30$ or $45\,\mathrm{GeV}^2$ in fixed-target, and $s = 200\,\mathrm{GeV}^2$ in collider mode, $M > 2\,\mathrm{GeV}$ and $\tau = x_1 x_2 = M^2/s > 0.1$.

The GSI kinematics is such that the asymmetries for double transverse Drell–Yan proton–antiproton processes are dominated by valence distributions and thus probe the product $\Delta_T q \times \Delta_T q$. At LO we can write

$$A_{TT}^{p\bar{p}} = \hat{a}_{TT} \frac{\sum_q e_q^2 [\Delta_T q(x_1, M^2) \Delta_T q(x_2, M^2) + \Delta_T \bar{q}(x_1, M^2) \Delta_T \bar{q}(x_2, M^2)]}{\sum_q e_q^2 [q(x_1, M^2) q(x_2, M^2) + \bar{q}(x_1, M^2) \bar{q}(x_2, M^2)]} \tag{5}$$

and $A_{TT}^{p\bar{p}}/\hat{a}_{TT}$ is found to be of order of 30%.[4,6]

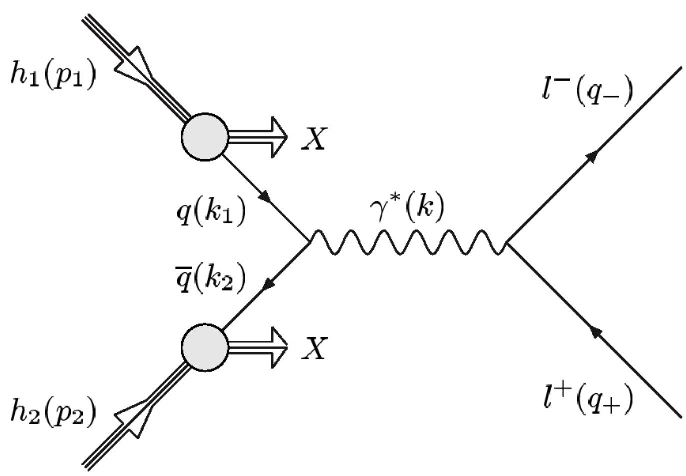

Figure 1. Drell–Yan process

At NLO the factorization formula of the cross-section for dilepton production in transversely polarized proton–antiproton scattering is [7,8]

$$\frac{\mathrm{d}\Delta_T\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi} = \sum_q e_q^2 \int_{\xi_1}^1 \mathrm{d}x_1 \int_{\xi_2}^1 \mathrm{d}x_2 \left[\Delta_T q(x_1,\mu^2)\Delta_T q(x_2,\mu^2) + \Delta_T\bar{q}(x_1,\mu^2)\Delta_T\bar{q}(x_2,\mu^2)\right] \frac{\mathrm{d}\Delta_T\hat{\sigma}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi}\,, \quad (6)$$

where μ^2 is the factorization scale, y is the rapidity of the dilepton pair and the momentum fractions ξ_1 and ξ_2 are defined as

$$\xi_1 = \sqrt{\tau}\,e^{y}, \qquad \xi_2 = \sqrt{\tau}\,e^{-y}, \qquad y = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}\,. \quad (7)$$

The NLO hard-scattering cross-section is

$$\begin{aligned}
\frac{\mathrm{d}\Delta_T\hat{\sigma}^{(1),\overline{\mathrm{MS}}}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi} &= \frac{2\alpha^2}{9sM}\,C_F\,\frac{\alpha_s(\mu^2)}{2\pi}\,\frac{4\tau(x_1x_2+\tau)}{x_1x_2(x_1+\xi_1)(x_2+\xi_2)}\,\cos(2\varphi)\\
&\times\Bigg\{\delta(x_1-\xi_1)\delta(x_2-\xi_2)\left[\frac{1}{4}\ln^2\frac{(1-\xi_1)(1-\xi_2)}{\tau}+\frac{\pi^2}{4}-2\right]\\
&+\delta(x_1-\xi_1)\left[\frac{1}{(x_2-\xi_2)_+}\ln\frac{2x_2(1-\xi_1)}{\tau(x_2+\xi_2)}+\left(\frac{\ln(x_2-\xi_2)}{x_2-\xi_2}\right)_+ +\frac{\ln(\xi_2/x_2)}{x_2-\xi_2}\right]\\
&+\frac{1}{2[(x_1-\xi_1)(x_2-\xi_2)]_+}+\frac{(x_1+\xi_1)(x_2+\xi_2)}{(x_1\xi_2+x_2\xi_1)^2}-\frac{3\ln\left(\frac{x_1x_2+\tau}{x_1\xi_2+x_2\xi_1}\right)}{(x_1-\xi_1)(x_2-\xi_2)}\\
&+\ln\frac{M^2}{\mu^2}\left[\delta(x_1-\xi_1)\delta(x_2-\xi_2)\left(\frac{3}{4}+\frac{1}{2}\ln\frac{(1-\xi_1)(1-\xi_2)}{\tau}\right)\right.\\
&\qquad\left.+\ \delta(x_1-\xi_1)\frac{1}{(x_2-\xi_2)_+}\right]\Bigg\}+\Big[1\longleftrightarrow 2\Big]. \qquad (8)
\end{aligned}$$

In order to predict asymmetries, some assumption for the transversity distributions is needed. For instance, we may take transversity equal to helicity at some low scale (as suggested by certain models)

$$\Delta_T f(x,\mu)=\Delta f(x,\mu)\quad\text{(minimal bound)} \qquad (9)$$

or, alternatively, saturation of the Soffer inequality [9]

$$2\,|\Delta_T f(x,\mu)|=f(x,\mu)+\Delta f(x,\mu)\,. \qquad (10)$$

We use NLO GRV input densities,[10] with starting scale $\mu = 0.63\,\mathrm{GeV}$. The relation between transversity and the GRV distributions is set at this scale. QCD evolution is performed via the appropriate NLO DGLAP equations.[11,12] In Fig. 2 we see that in the energy range relevant for the PAX experiment the asymmetries are around 35%. From Fig. 3 we see that in the case of the Soffer bound the asymmetries are systematically larger than the asymmetries obtained in the case of the minimal bound. In Fig. 4 we display the asymmetry at larger M, where it grows up to 45% (but one should recall that the cross-section falls rapidly as M increases). Applying the constraint $\Delta_T f(x,\mu) = \Delta f(x,\mu)$ at, say, $1\,\mathrm{GeV}$ instead of $0.63\,\mathrm{GeV}$ would produce slightly larger asymmetries; this is due to QCD evolution effects since $\Delta_T f(x,\mu)$ is less suppressed by evolving from $1\,\mathrm{GeV}$ than from $0.63\,\mathrm{GeV}$. The comparison between LO and NLO results is shown in Fig. 5, where one sees that NLO corrections have very little affect on the asymmetries.

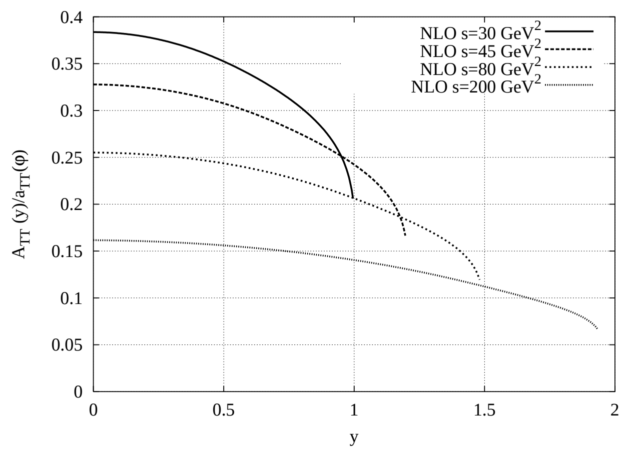

Figure 2. $A_{TT}(y)/\hat{a}_{TT}(\varphi)$ at NLO, with M integrated from 2 to 3 GeV using GRV input with the minimal bound $\Delta_T q(x,\mu) = \Delta q(x,\mu)$.

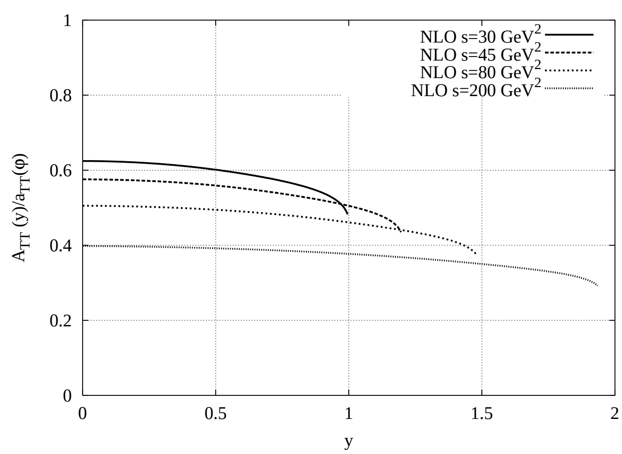

Figure 3. $A_{TT}(y)/\hat{a}_{TT}(\varphi)$ at NLO, with M integrated from 2 to 3 GeV using GRV input and saturating the Soffer bound.

3. Dilepton production via the J/ψ resonance in the GSI regime

To achieve a higher counting rate, one may exploit the J/ψ peak, where the cross-section is two orders of magnitude larger. If J/ψ production is dominated by $q\bar{q}$ annihilation channel, the corresponding asymmetry has the same structure as in the continuum region, since the J/ψ is a vector

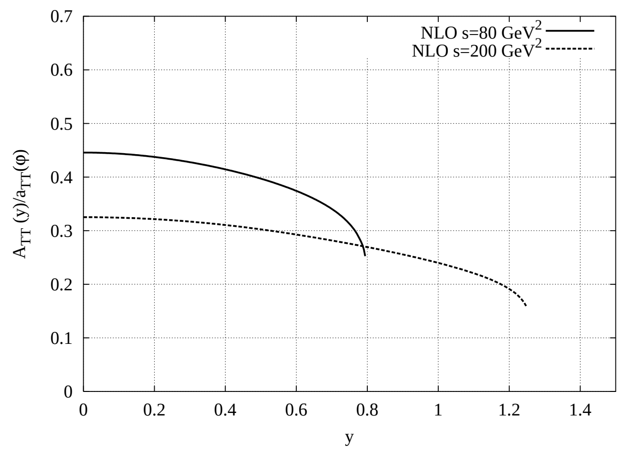

Figure 4. $A_{TT}(y)/\hat{a}_{TT}(\varphi)$ at NLO with M integrated from 4 to 7 GeV using GRV input with the minimal bound.

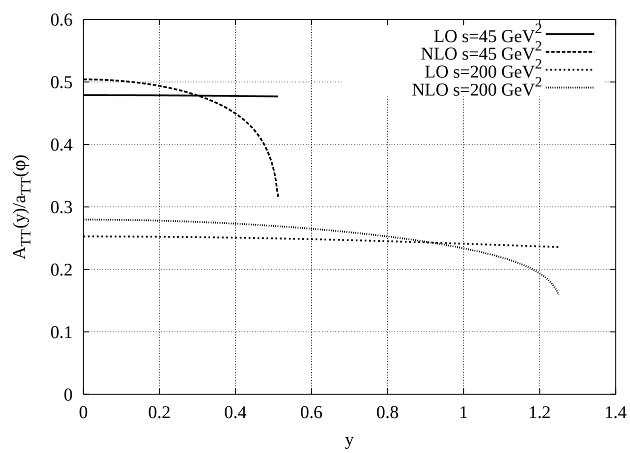

Figure 5. $A_{TT}(y)/\hat{a}_{TT}(\varphi)$ at LO (solid curve) *vs.* NLO (dashed curve) at $M = 4\,\mathrm{GeV}$ and $s = 45\,\mathrm{GeV}^2$ and $A_{TT}(y)/\hat{a}_{TT}(\varphi)$ at LO (dotted curve) *vs.* NLO (dot-dashed curve) at $M = 4\,\mathrm{GeV}$ and $s = 200\,\mathrm{GeV}^2$ using GRV input with the minimal bound.

particle and the $q\bar{q} - J/\psi$ couplings are similar to $q\bar{q} - \gamma^*$.[4] SPS data[13] show the $p\bar{p}$ cross-section for J/ψ production at $s = 80\,\mathrm{GeV}^2$ to be about 10 times larger than the corresponding pp cross-section, indicating the dominance of the $q\bar{q}$ annihilation mechanism. Thus, the helicity structure of the asymmetries is preserved and, replacing the couplings in Eq. (5), we can

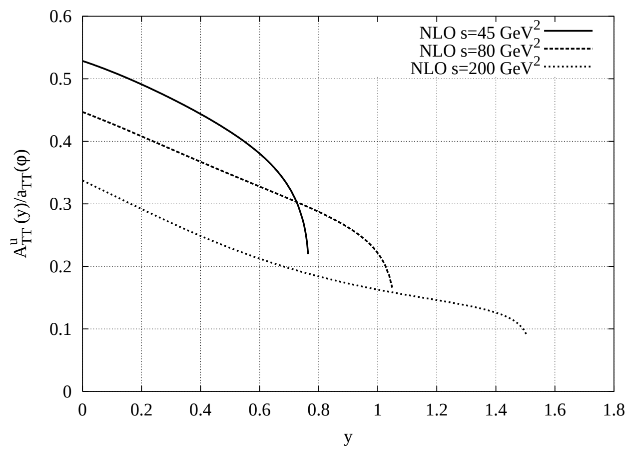

Figure 6. The double transverse-spin asymmetry in the J/ψ resonance region for various c.m. energies. As usual, the minimal bound is used for the input distributions.

write

$$A_{TT}^{J/\psi} = \hat{a}_{TT} \times \frac{\sum_q (g_q^V)^2 \left[\Delta_T q(x_1, M^2)\Delta_T q(x_2, M^2) + \Delta_T \bar{q}(x_1, M^2)\Delta_T \bar{q}(x_2, M^2)\right]}{\sum_q (g_q^V)^2 \left[q(x_1, M^2)q(x_2, M^2) + \bar{q}(x_1, M^2)\bar{q}(x_2, M^2)\right]} \tag{11}$$

In the large x_1, x_2 region the u and d valence quarks dominate and, since the $q\bar{q} - J/\psi$ coupling is the same for u and d quarks, the asymmetry becomes

$$A_{TT}^{J/\psi} \simeq \hat{a}_{TT} \frac{\Delta_T u(x_1, M^2)\Delta_T u(x_2, M^2) + \Delta_T d(x_1, M^2)\Delta_T d(x_2, M^2)}{u(x_1, M^2)u(x_2, M^2) + d(x_1, M^2)d(x_2, M^2)} \,. \tag{12}$$

The condition $\Delta_T u(x) \gg \Delta_T d(x)$, satisfied by all models at large x, permits a further simplification and one obtains

$$A_{TT}^{J/\psi} \simeq \hat{a}_{TT} \frac{\Delta_T u(x_1, M^2)\Delta_T u(x_2, M^2)}{u(x_1, M^2)u(x_2, M^2)} \,. \tag{13}$$

The J/ψ asymmetry is then essentially the DY asymmetry evaluated at $M_{J/\psi}$ and, for $s = 80\,\mathrm{GeV}^2$, lies in the range 0.25–0.45 (see Fig. 6). Inasmuch as the gg fusion diagram may be neglected, as old $p\bar{p}$ data suggest, this remains true at NLO (i.e. considering gluon radiation).

4. Threshold resummation

The kinematic region corresponding to $M \approx 1 - 4\,\mathrm{GeV}$ and with a centre-of-mass energy $s \approx 30\,\mathrm{GeV}^2$ is not properly contained in the domain of perturbative QCD, (i.e. factorization, parton model etc.). Thus, depending on kinematics, higher-order corrections to the cross-sections may be important and must be well understood.

For the sake of simplicity, we shall merely sketch what occurs, with little quantitative detail. The factorization theorem for the hadronic cross-section in terms of twist-2 parton densities is not exact, but holds only to the leading power of M, and the corrections generally increase as τ increases. In the region $z = \tau/(x_1 x_2) \simeq 1$ the kinematics is such that virtual and real-emission diagrams become strongly unbalanced (real-gluon emission is suppressed) and in these conditions there are large higher-order logarithmic corrections to the partonic cross-section of the form

$$\alpha_s^k \frac{[\ln(1-z)]^{2k-1}}{(1-z)} \tag{14}$$

The region $z \approx 1$ is dominant in the kinematic regime relevant for GSI, hence the large logarithmic contributions need to be resummed to all orders in α_s. NLL-resummed perturbation theory has been extensively studied [14] and resummation corrections for A_{TT} are found to be less than 10% and rather dependent on the infrared cut-off for the soft gluon emission.

5. Conclusions

In the GSI regime Drell–Yan double transverse-spin asymmetries are sizable, of the order of 30%, and are not spoiled by NLO (and resummation) effects. Transverse asymmetries for J/ψ production at moderate energies are expected to be similar (with the advantage of much higher counting rates). Transversely polarized antiproton experiments at GSI will thus provide an excellent window onto nucleon transversity.

Acknowledgments

We would like to thank M. Anselmino, N.N. Nikolaev and our colleagues of the PAX collaboration for prompting the study reported here and for various useful discussions. This work is supported in part by the Italian Ministry of Education, University and Research (PRIN 2003).

References

1. V. Barone, A. Drago and P.G. Ratcliffe, *Phys. Rep.* **359** (2002) 1.
2. V. Barone, T. Calarco and A. Drago, *Phys. Rev.* **D56** (1997) 527.

3. O. Martin, A. Schäfer, M. Stratmann and W. Vogelsang, *Phys. Rev.* **D57** (1998) 3084.
4. M. Anselmino, V. Barone, A. Drago and N.N. Nikolaev *Phys. Lett.* **B5** (2004) 97.
5. PAX Collaboration, V. Barone *et al.*, "Antiproton–Proton Scattering Experiments with Polarization", Technical Proposal, hep-ex/0505054 (2005).
6. A. Efremov, K. Goeke and P. Schweitzer, *Eur. Phys. J.* **C35** (2004) 207.
7. O. Martin, A. Schäfer, M. Stratmann and W. Vogelsang, *Phys. Rev.* **D60** (1999) 117502.
8. A. Mukherjee, M. Stratmann and W. Vogelsang, *Phys. Rev.* **D67** (2003) 114006.
9. J. Soffer, *Phys. Rev. Lett.* **74** (1995) 1292.
10. M. Glück, E. Reya and A. Vogt, *Eur. Phys. J.* **C5** (1998) 461; M. Glück, E. Reya, M. Stratmann and W. Vogelsang, *Phys. Rev.* **D63** (2001) 094005.
11. A. Cafarella and C. Corianò, *Comput. Phys. Commun.* **160** (2004) 213.
12. A. Cafarella, C. Corianò and M. Guzzi, *JHEP* **0311** (2003) 059.
13. M.J. Corden, *Phys. Lett.* **B98** (1981) 220.
14. H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, *Phys. Rev.* **D71** (2005) 11407.